Sl 7/10

United States
Environmental Protection
Agency

Municipal Environmental Research
Laboratory
Cincinnati OH 45268

Research and Development

EPA-600/S2-81-227 Dec. 1981

EPA

NEWARK PUBLIC LIBRARY

FEB 1 1982

U. S. GOVT. PUBS.
DEPOSITORY 376

Project Summary

Performance of Activated Sludge Processes: Reliability, Stability and Variability

Salar Niku, Edward D. Schroeder, George Tchobanoglous, and Francisco J. Samaniego

The objective of this research study was to statistically analyze the performance of a large number of activated sludge processes and to develop methods and procedures for introducing reliability and stability concepts into design and operation of wastewater treatment plants. Variations in the daily effluent quality of 43 activated sludge processes were examined. From an analysis of the data, it was found that the effluent variables are not distributed symmetrically, and generally their distributions are skewed further to the right than to the left of the most frequent value. The lognormal distribution was found to fit the observed effluent biochemical oxygen demand (BOD) and suspended solids (SS) data most consistently.

Using the lognormal distribution and a coefficient of reliability (COR), a probabilistic model and design tables and graphs have been developed for predicting achievable effluent BOD and SS concentrations. Mean constituent values are correlated to selected standards with the COR. The proposed model can be used in the design of a treatment process expected to perform at a certain reliability and/or to estimate the reliability of an operating treatment plant. Validity of the reliability model in prediction of effluent quality performance has been verified.

The stability of various activated sludge processes was examined using several statistical measures. Stability is defined as a measure of the daily variations from the annual mean. The standard deviation was found to be the most appropriate indicator of stability. A standard deviation of 10 g/m^3 was selected as stability cut-off point on the basis of a qualitative examination of the data. Plants with effluent values below 10 g/m^3 are considered stable; plants with values greater than 10 g/m^3 are considered unstable. The effect of plant size and process type on stability was also examined.

Correlation and regression analyses have been used to investigate the causes of effluent quality variability and to identify the extent of the factors contributing to this variability. The contribution of several variables to the observed effluent BOD and SS variations were examined. No single variable or group of variables was found that could be used to characterize the variability of effluent quality for all plants in general. However, the method may be applied to data from each individual plant to determine the principal factors responsible for effluent quality variations.

The appropriateness of effluent standards as they are currently stated was discussed, and the use of the geometric mean as a measure of central tendency of daily effluent quality data was recommended for setting discharge standards. This recommendation is based on the fact

EP 1.89/2:

READEX FICHE

that effluent concentration values are distributed lognormally and that the geometric mean of lognormal data has known probabilistic behavior and a meaningful interpretation.

Design procedures and/or discharge requirements should be based on a recognition of the variability of process performance; that is, they should be stochastic in character. An approach is presented that can be used to design a process stochastically when the effluent standards are deterministic in nature.

This Project Summary was developed by EPA's Municipal Environmental Research Laboratory, Cincinnati, OH, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

In recent years regulatory agencies have become more aware of the need to continually examine the performance characteristics of wastewater treatment plants. Since 1970, explicit performance standards have been placed on most biological treatment processes in the United States. The Federal Water Pollution Control Act Amendments of 1972 (P.L. 92-500) were written with the intent of restoring and maintaining the chemical, physical, and biological integrity of the Nation's water. To achieve these objectives, the U.S. Environmental Protection Agency (EPA) has set a minimum standard of effluent quality as that attainable by the application of biological treatment processes. The standards for secondary treatment were to be met by 1977, and Best Practicable Waste Treatment Technology is to be achieved by 1983. Comprehensive standards have not been established because of the lack of information on the performance capabilities of operating plants.

It must be recognized that effluent biochemical oxygen demand (BOD) and suspended solids (SS) concentrations from biological treatment processes are highly variable. Input loads, environmental conditions, operational parameters, and human factors may affect or be the cause of this variability. All of these factors are themselves subject to fluctuations in magnitude, composition, and simultaneous occurrence.

Most wastewater treatment facilities are designed with limited information as to the nature and magnitude of these variations. The usual procedure is that the flow records, if existing, are analyzed and some peak flow rate established. An estimate is made of the corresponding BOD and SS mass loadings (with little or no rational basis for the decision other than experience). Design parameters such as mean cell residence time, sludge wastage, and sludge recycle rate are established on the basis of past experience and intuition. The process is then designed based on empirical models in which steady state conditions are assumed, with kinetic coefficients obtained from the literature.

Kinetic models currently available are based on mean values and variations in performance cannot be predicted using these models. Seldom, if ever, is the stochastic nature of these variables and parameters incorporated into the design process. This is because techniques for incorporating information on performance variability into the design and also in the setting of discharge standards have not yet been implemented.

Objective

The basic purpose of this study was to develop information that can be used by the designer and operator of a wastewater treatment plant in evaluating and predicting the performance of a biological treatment process with respect to effluent quality and by the regulatory agencies in preparing reasonable, effective, and technically sound discharge requirement orders.

Four subjects were studied in this report:

1. Performance of a large number of activated sludge processes was analyzed and the reliability of each was determined. A reliability model was developed that can be used to predict process performance of plants under design or currently under operation.
2. Stability of activated sludge processes based on statistical measures was studied with the objective of introducing a method that can be used to define and compare the stability of plants within and among each.
3. For the reliability and stability study, each treatment plant was considered as a "black box"; meaning, all variables affecting process performance were considered to be uncontrolled and unknown. Reliability and stability models were developed based only on discharge effluent data. In this part of the study the effect of various factors on effluent quality was studied with the objective of determining the nature, sources, and the extent of the variability in effluent quality and to identify factors contributing to this variability through statistical analysis of operating data.
4. Appropriateness of effluent discharge standards as they are currently established was examined and discussed. An alternative approach of using geometric mean as opposed to arithmetic mean is recommended for defining the central tendency of effluent BOD and SS concentrations and for setting effluent discharge standards.

General Appraoch

The scope of this project included collection and analysis of performance and operational data from 43 activated sludge wastewater treatment plants located throughout the United States. Evaluation of the performance of these processes in terms of reliability, stability, and variability was based on the analysis of these data. The results of this study for activated sludge processes are reported in this summary report.

Location by state, process type, and plant size are shown in Table 1. The selected treatment plants represent a range of geographic locations and environmental conditions throughout the United States and range in flow from less than 1 mgd to more than 200 mgd.

Reliability of Activated Sludge Processes

Reliability Concept

Reliability of a system can be defined as "the ability to perform the specified requirements free from failure" or "the probability of adequate performance for a least specified period of time under specified conditions." A treatment plant is completely reliable if process performance response has no failure (e.g., discharge requirement violations). Failure of a treatment process is realized when the required effluent discharge satndards are exceeded, i.e.,

"Failure" = effluent concentration > effluent requirements

Table 1. Activated Sludge Treatment Plants Studied

Plant Number	Plant Location	Year	Type of Process	Average Flow (mgd)
1	Michigan	76	Complete mix	14.2
2	California	7-75/6-76	Conventional	100.0
3	California	76	Complete mix/contact stab.	16.2
4	Wisconsin	76	Contact stabilization	23.7
5	Illinois	76	Step feed	69.7
6	Illinois	76	Conventional	66.2
7	Illinois	76	Conventional	69.1
8	Maryland	76	Step feed	15.2
9	New York	77	Complete mix	18.6
10	Alabama	6-76/5-77	Aerated lagoon	23.6
11	Michigan	10-76/9-77	Complete mix	0.74
12	Virginia	76	Conventional/step feed	15.8
13	Alabama	7-76/6-77	Conventional/step feed	10.5
14	Illinois	76	Conventional	2.2
15	Illinois	76	Step feed	3.3
16	California	75	Step aeration	6.3
17	California	76	Step aeration	2.4
18	California	76	Step aeration	29.0
19	California	76	Step aeration	7.1
20	Illinois	76	Conventional	209.0
21	Illinois	76	Conventional	189.0
22	Illinois	76	Conventional	188.0
23	Illinois	76	Step feed	185.0
24	Michigan	73	Conventional	1.9
25	Michigan	74	Conventional	2.1
26	Michigan	75	Conventional	2.1
27	Michigan	76	Conventional	2.3
28	Michigan	77	Conventional	2.1
29	Michigan	77	Conventional	9.5
30	Michigan	77	Conventional	9.5
31	Connecticut	76	Conventional	3.8
32	California	76	Plug flow/Kraus	47.1
33	Ohio	76	Contact stabilization	2.8
34	Nevada	75	Conventional/tapered	17.0
35	Kansas	75	Contact stabilization	10.4
36	Washington	76	Conventional/step feed	30.8
37	California	76	Complete mix/step feed	13.9
38	Michigan	10-76/10-77	Step feed	17.3
39	Michigan	77	Conventional/contact stab.	33.3
40	Michigan	12-76/11-77	Extended aeration	0.56
41	Michigan	01-77/10-77	Conventional	26.9
42	Wisconsin	76	Conventional	81.6
43	Wisconsin	76	Conventional	54.0

Because of numerous uncertainties underlying the design and operation of a wastewater treatment plant, there is some risk of failure (discharge requirement violation) that is unavoidable. This risk should be recognized and wastewater treatment plants ought to be designed on the basis of an acceptable measure of risk (of violation).

In a technical definition, the essential concept of reliability is "probabilty of success" or "probability of adequate performance"; i.e., the percent of the time that effluent concentration meets the requirements.

Reliability = 1 - P(failure) =1 - P (effluent concentration > requirements)

The probability of failure is extremely sensitive to the distribution function of effluent concentration. Thus, to develop a reliability model, first the distribution of effluent concentration should be modeled. Assuming the distribution of effluent concentration is known, then, the reliability of the plant can be computed.

The designer of a treatment process should first select an appropriate level of process performance; that is, he must decide how large a probability of failure he can accept. The classical approach to this question is to apply statistical-economic decision theory. Plant costs (both capital and operating) rise with increasing performance requirements. On the other hand, lower expectations in water quality or acceptance of a higher probability of violations will result in adverse effects on water quality downstream. Thus, the level of reliability and the effluent discharge standards directly affect plant economics. The degree of reliability (probability of adequate performance) should be selected in such a way that these costs are minimized.

Effluent Concentration Distribution

Statistical analyses of the data summarized in the full report show that the performance of the plants on an annual basis is quite variable. Effluent concentration of BOD and SS varied significantly among the plants. Mean effluent BOD and SS for plants studied ranged from 1.9 to 85.6 g/m^3 and 2.5 to 80.1 g/m^3, respectively. On the average, effluent SS concentration and its variation was greater than the corresponding effluent BOD values.

Histograms of the effluent BOD and SS data were plotted, and the data distributions were analyzed. The data were generally not symmetrical and were all skewed to the right (positive skewness coefficient). It was found that in most plants, effluent BOD and SS data are not normally distributed, whereas a lognormal distribution consistently fits the observed effluent BOD and SS data.

The lognormal probability distribution is one commonly used in civil engineering practice and seems to have been adopted originally to produce a better fit to skewed data by using this simple transformation of the familiar normal distribution. The lognormal distribution has an important justification from the normal distribution, in that, fluctuations from the mean are proportional rather than additive. All currently used kinetic models for the activated sludge process result in multiplicative expressions for effluent BOD. It is thus not unreasonable to expect effluent BOD to have a lognormal distribution.

The Kolomogorov-Smirnov (K-S) test was used to test the goodness-of-fit of the data to lognormal distribution. It was concluded that the hypothesized log-

normal model should not be rejected for more than two-thirds of the plants at significant levels of 1 percent. Generally, the results of the K-S test (not reported in this summary report) suggest that a lognormal distribution provides a reasonable description of the effluent BOD and SS data.

Process Reliability

Reliability of a treatment plant is based on knowledge of process behavior. Because of variations in performance, a treatment plant should be designed to produce an average effluent concentration below the discharge standards. The question is, what mean value should be used to guarantee an effluent concentration consistently less than a standard with a certain reliability? A coefficient of reliability (COR) may be introduced that relates mean constituent values (i.e. the design values) to the standard that must be achieved on a probability basis. For example, if a 30-g/m^3 standard is to be achieved 90 percent of the time, the process must be designed to achieve a particular mean effluent concentration. The mean constituent value, m_x, is then obtained from Equation 1:

$$m_x = (COR)\, X_s \qquad (1)$$

where X_s = a fixed standard.

Suppose that for some probability of failure α between zero and one but presumably near zero, a process is to be designed for which the observed lognormal variable X has the property that

$$P(X \leq X_s) = 1 - \alpha \qquad (2)$$

The problem of interest is to develop an expression for the COR that can be used to compute the necessary mean value of the process that guarantees that reliability level $1-\alpha$, given a known standard X_s.

Knowing the effluent BOD and SS data are lognormally distributed, the COR was modeled using the properties of lognormal distribution. Development of the COR model is not reported here and may be found in the main report. After substitution of properties of lognormal distribution, Equation 1 results in the following:

$$m_x = (V_x^2 + 1)^{1/2} \exp\{-Z_{1-\alpha} [Ln(V_x^2 + 1)]^{1/2}\}(X_s) \qquad (3)$$

where

$$COR = (V_x^2 + 1)^{1/2} \exp\{-Z_{1-\alpha} [Ln(V_x^2 + 1)]^{1/2}\} \qquad (4)$$

X — BOD or SS concentration

m_x — mean value of X

V_x — coefficient of variation of X defined as the ratio of standard deviation, $\bar{\sigma}_x$, to the mean, m_x (e.g., $V_x = \frac{\bar{\sigma}_x}{m_x}$).

exp — exponential

$Z_{1-\alpha}$ — standardized normal variate at $1-\alpha$ degree of probability

$1-\alpha$ — probability of success
Note: values of probability $1-\alpha$ and the associated percentiles, $Z_{1-\alpha}$, are available in any standard statistical text. For instance at reliability level of $1-\alpha$ = 0.95, $Z_{1-\alpha} = 1.645$. This means there is 95 percent probability that the value X would be less than $m_x + 1.645\,\bar{\sigma}_x$. Some selected values of $1-\alpha$ and $Z_{1-\alpha}$ are shown in Table 2.

X_s — a fixed standard, e.g., X_s = 30 g/m^3

The COR (Equation 4) relates the mean constituent value, m_x, to the standard X_s for reliability level of $1-\alpha$. Note that COR is expressed based on properties of the original data and not the logarithm of the data.

Reliability Based Design of Activated Sludge Processes

Values of the COR for effluent concentrations for different coefficients of variation (V_x) at different levels of reliability are plotted in Figure 1. The reliability model (Equation 4 or Figure 1) has a significant potential application in design. Values of COR given in Equation 4 or Figure 1 may be used in design of a treatment plant expected to perform at a certain reliability level. The coefficient of variation for the effluent concentration should be estimated first. Selection of the appropriate design value of the coefficient of variation, V_x, must be based on reasonable expectation of performance (i.e., experience), just as are other design parameters now in use (e.g., hydraulic residence time and overflow rate). This may be done from past experience or using the results from other similar treatment plants such as those shown later in this summary. Implications derived from the reliability model are best described by an example:

To have 95 percent reliability that the effluent BOD concentration will be equal to or less than a certain standard X_s, when V_x for the plant is estimated to be 0.70, the plant should be designed for the mean value equal to or less than 0.43 X_s. (If X_s = 30 g/m^3; then average BOD = 0.43 x 30 = 12.9 g/m^3 or less. Similarly, for a less stringent standard of X_s = 40 g/m^3; average BOD = 0.43 x 40 = 17.2 g/m^3 or less).

As would be expected, the mean value of required effluent concentration varies inversely with reliability level and with the coefficient of variation in effluent concentration.

Estimation of Reliability of Activated Sludge Processes

The reliability model (Equation 3) may be rearranged to estimate the reliability of a treatment plant under operation when the mean and standard deviation for the plant are known (Equation 5). This is done by computing the percentile value $Z_{1-\alpha}$

$$Z_{1-\alpha} = -\frac{Ln\left[\frac{m_x}{X_s}(V_x^2 + 1)^{-1/2}\right]}{Ln\left[(V_x^2 + 1)^{1/2}\right]} \qquad (5)$$

and reliability is determined using the standard normal table (e.g., Table 2).

For example, the reliability of a plant operating with a mean value of 0.6 X_s and a V_x = 0.70 is 87 percent. In other words, in a long-run operation, about 13 percent of the observed effluent variables would exceed 30 g/m^3 in a plant operating with a mean value of 18 g/m^3 and standard deviation of 12.6 g/m^3 (V_x = 0.70). Figure 1 may be used instead of Equation 5.

Verification of Results

To support the validity of the model in prediction of effluent quality, the percent of the time that effluent concentration exceeded 30 g/m^3 was computed for 1 year of data in all plants. This percent of exceedance was also predicted using the reliability model (Equation 4, or Figure 1) based on the lognormal assumption. The predicted

Table 2. *Cumulative Probabilities of the Standard Normal Distribution*

Cumulative Probability $1-\alpha$	$Z_{1-\alpha}$
99.9	3.090
99	2.326
98	2.054
95	1.645
92	1.405
90	1.282
80	0.842
70	0.525
60	0.253
50	0

values (not included in the summary report) were very comparable with the measured values.

Stability of Activated Sludge Processes

Conventional criteria and design procedures employed in the design of municipal and industrial wastewater processes are based on the simplified assumption of steady-state conditions. In practice, activated sludge systems are seldom operated under steady state conditions. Effluent quality depends on input loads, environmental conditions, in-plant biological and operational variables as well as many other unexpected perturbations beyond operational control. Designing a treatment process is thus a multivariate problem. Fluctuations in input loads and environmental conditions, nature of the wastewater, introduction of toxic materials, and mechanical failure of the system as well as human factors may frequently cause process upset and instability that may have adverse effects on quality.

Stability Measure

Stability may be thought of as the property of adherence to a reference or norm. In the case of wastewater treatment, the best reference value for stability appears to be the annual mean constituent concentration. One complete cycle of weather and a monitoring period long enough to damp the effects of short term variations is reflected in the annual mean value. Variations from the mean on a day-to-day (or week-to-week or month-to-month) basis then provide a measure of stability.

Since stability is a measure of variation from the mean, a standard quantitative measure of variation

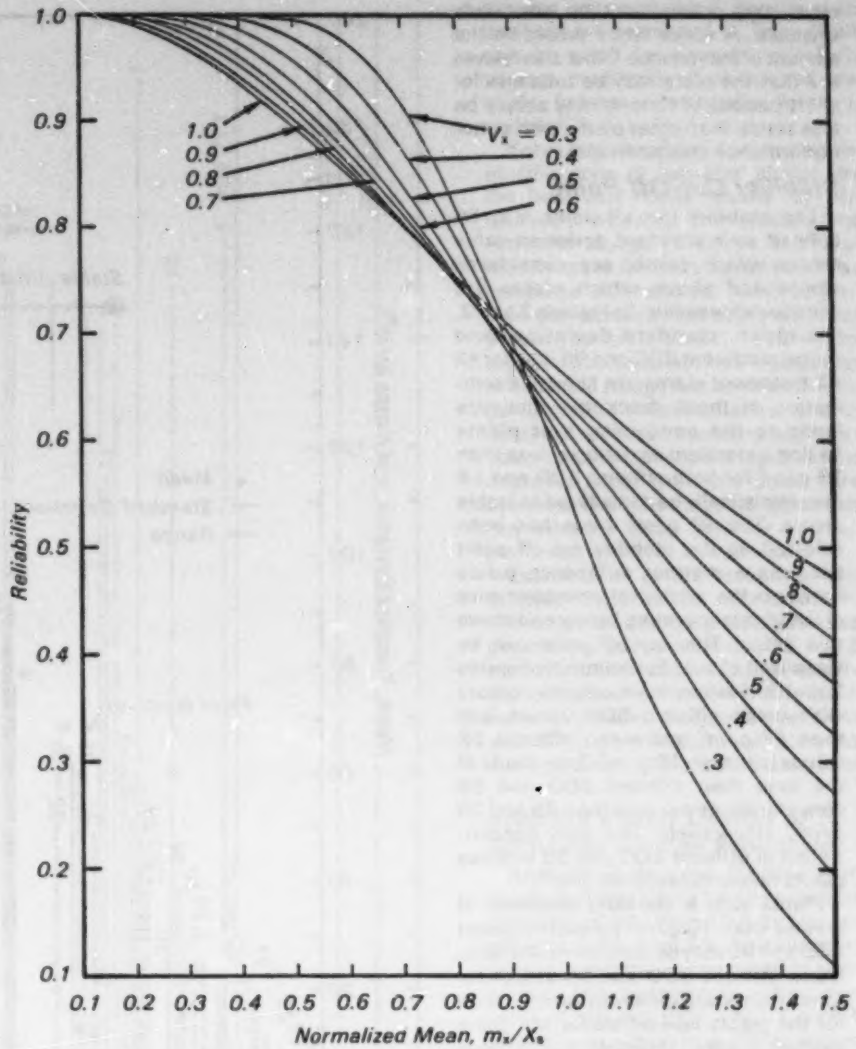

Figure 1. *Reliability versus normalized mean for different coefficients of variations.*

(stability indicator) is of special interest. The stability indicator may be used as a tool to evaluate and compare the relative of different plants and to examine the effects that various design and operation procedures may have on process stability. Several such indicators are available.

Among those available stability indicators, standard deviation has been selected as the most appropriate indicator of wastewater treatment plant stability. This is because the standard deviation is theoretically a measure of dispersion, and practically it is the most familiar and simplest term among all other measures of stability.

Stability is usually defined in relative terms. For example, in comparing the stability of two treatment plants, the plant with less effluent quality variation is considered more stable. Stability may also be defined in absolute terms where a valid time deterministic modél is available. For instance, if the monthly variance of effluent quality of a plant continuously increases each month (or any other time period), then, that plant is an unstable one in absolute terms. When variance changes randomly, the

plant may or may not be absolutely unstable. A major factor would be the amount of the variance. Other alternatives are that the plant may be unstable for short periods of time or may simply be less stable than other plants with better performance characteristics.

Stability Cut-Off Point

The stability cut-off point may be defined as a standard deviation value below which plants are considered stable and above which plants are considered unstable. In Figures 2 and 3, the mean, standard deviation, and range of effluent BOD and SS data for all 43 treatment plants are shown. Examination of these descriptive statistics leads to the conclusion that plants having a standard deviation of less than 10 g/m^3 for both effluent BOD and SS may statistically be considered as stable plants. The 10 g/m^3 value has been selected as the stability cut-off point because a distinct difference exists between the statistical characteristics of the plants operating below and above this value. This cut-off point can be visualized clearly by examining Figures 2 and 3. Stable plants usually operate with mean effluent BOD values less than 17 g/m^3 and mean effluent SS values less than 15 g/m^3. Two-thirds of the time their effluent BOD and SS concentrations are less than 25 and 20 g/m^3, respectively. The daily concentration of effluent BOD and SS in these plants rarely exceeds 60 g/m^3.

Plants with a standard deviation of greater than 10 g/m^3 for both effluent BOD and SS may be considered unstable. Mean effluent BOD and SS values for these plants are generally greater than for the plants labeled stable, but some overlap occurs. Unstable plants have annual mean BOD and SS values as low as 16 and 10 g/m^3, respectively. The maximum daily BOD and SS concentrations of these plants are usually much greater than stable plants and exceed 90 and 130 g/m^3, respectively.

Examination of the results of this analysis also leads to the conclusion that generally, effluent SS shows more variation than effluent BOD and is expected to be a more significant factor in determining instability. Process upsets may happen more often due to high values of SS than to high values of BOD in the final effluent. To achieve the same level of stability for both BOD and SS, a plant should be designed to produce an average effluent SS less than effluent BOD.

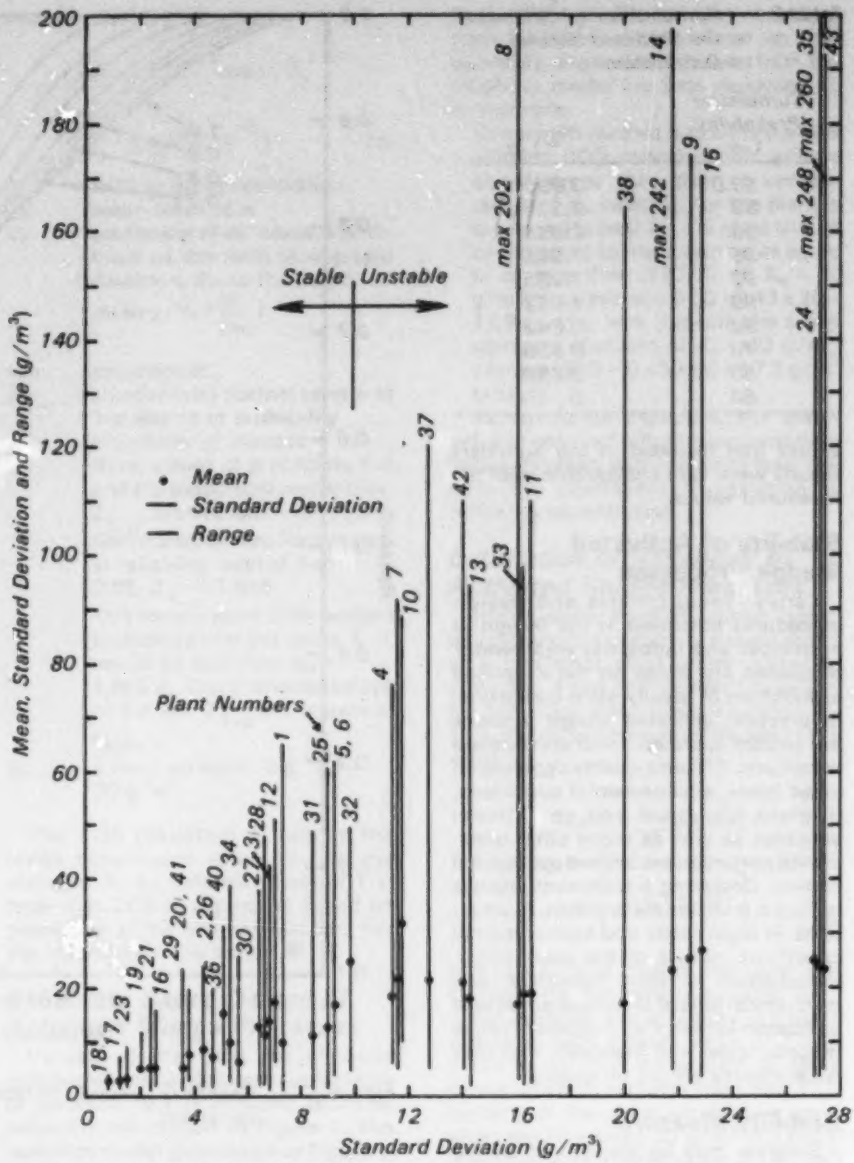

Figure 2. Mean, standard deviation, and range of effluent BOD concentration in different treatment plants.

The Effect of Plant Size on Stability

Correlations between annual mean flow (as an indication of plant size) with annual mean and standard deviation of effluent BOD and SS were determined to examine the significance of plant size on effluent quality and stability. Correlation coefficients of r = 0.19 and 0.17 were determined between annual mean flow with annual mean effluent BOD and SS, respectively; and coefficients of r = 0.23 and 0.16 were determined with standard deviations of effluent BOD and SS, respectively. The conclusion from these results is that there is poor correlation between plant size and effluent quality; that is larger plants do not necessarily produce better quality effluent than smaller plants. Generally, there appears to be no relationship between plant size and stability.

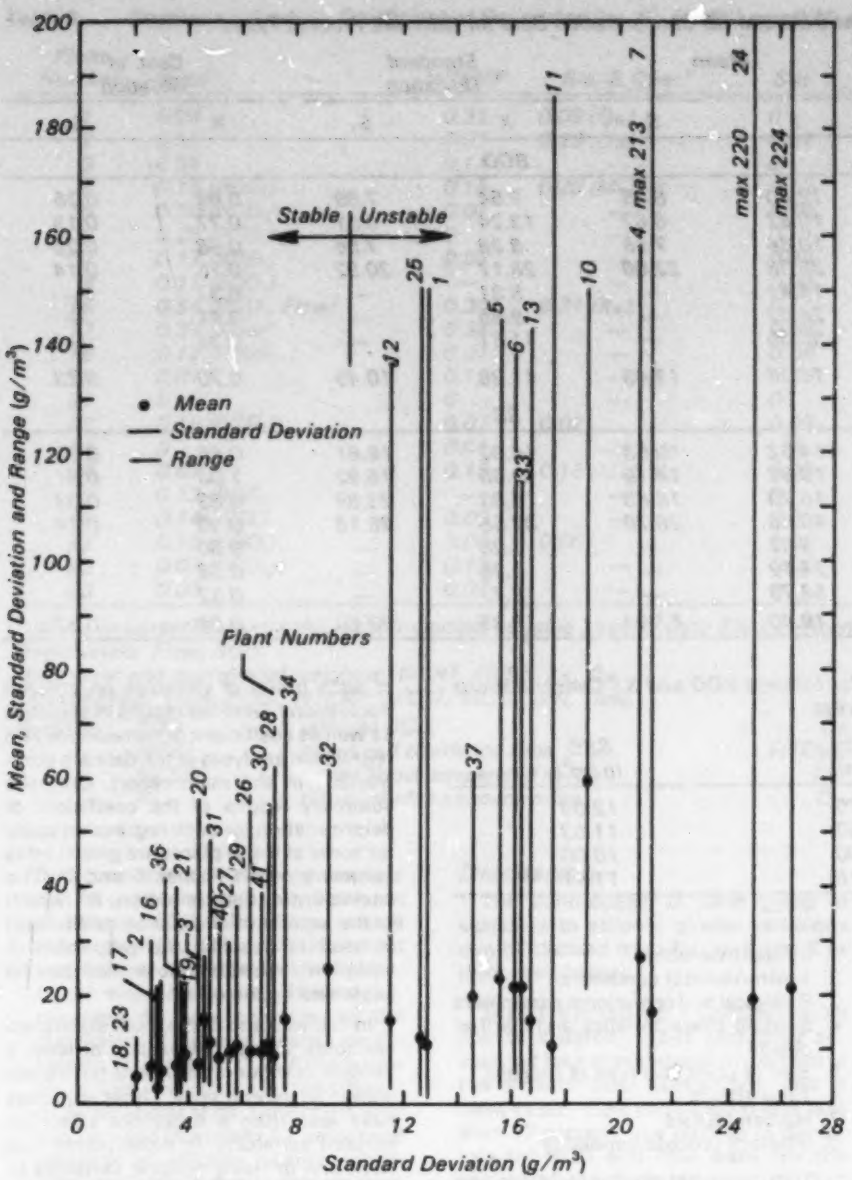

Figure 3. Mean, standard deviation, and range of effluent suspended solids concentration in different treatment plants.

The Effect of Process Type on Stability

Activated sludge processes are flexible systems and have been adopted to a number of different flow schematics. Ideally, the most appropriate process design will reduce the variability of effluent quality significantly.

To examine that relationship between process type and stability, activated sludge treatment plants under study were grouped by process modification type and then were compared with each other. The data set included 18 conventional 13 step-feed and step-aeration, 5 complete-mix, 4 contact-stabilization, 1 extended-aeration, 1 kraus, and 1 aerated lagoon. The average (X) and standard deviation (S_x) of the annual means, standard deviations, and coefficients of variation of each type of process were computed. Results of the analysis are presented in Table 3 and can be used for comparison of the various modifications of the activated sludge process in terms of performance and stability.

Generally, step-feed or step-aeration modifications of activated sludge give the best year-round results for BOD removal, whereas the conventional activated sludge gives the best year-round results for SS removal. In terms of combined BOD and SS removal, step-feed and conventional activated sludge processes give similar year-round results. The complete-mix modification of activated sludge has somewhat lower performance characteristics, and the contact-stabilization process appears to have considerably lower performance characteristics than the other three systems. The other process types were not included since data for only one plant was available in each case.

Examination of the results for each process leads to the conclusion that conventional and step-feed processes generally produce effluent BOD and SS concentrations below average, and that the complete-mix and contact-stabilization processes produce effluent BOD and SS concentrations greater than average when all plant data are pooled.

Stability Based Design of Activated Sludge Processes

Analysis of data has resulted in the conclusion that plants having a standard deviation of less than 10 g/m³ for both effluent BOD and SS concentrations may be statistically considered as stable plants. The question is, what mean value of effluent BOD and SS concentration may result in a stable process while considering variations in effluent quality? Variations in effluent quality are described by the coefficient of variation, V_x. This coefficient may be estimated for each process type using the results of Table 3.

To produce a stable effluent quality (i.e., a process with a standard deviation of equal to or less than 10 g/m³), the process should be designed for a mean value equal to or less than $X = S_x/V_x$, where S_x = 10 g/m³. These values for different process types are shown in Table 4. To achieve stability, activated sludge processes should be designed for an effluent BOD concentration equal to or less than 13 to 15 g/m³ and an effluent SS concentration equal to or less than 10 to 12 g/m³.

Table 3. Statistics of the Annual Effluent BOD and SS Concentration Data for Different Process Types

Process Type	No. of Plants	Mean		Standard Deviation		Coef. of Variation	
		$\bar{X}$	$S_{\bar{x}}$	X	S_x	X	S_x
				BOD			
Conventional	18	12.80	6.85	9.54	7.99	0.69	0.25
Complete-mix	5	16.82	6.67	13.24	6.51	0.77	0.13
Step-feed/aeration	13	10.84	7.68	8.28	7.56	0.68	0.25
Contact stabilization	4	38.38	32.08	28.17	20.92	0.76	0.14
Extended aeration	1	14.41	—	5.31	—	0.37	—
Kraus	1	24.02	—	9.85	—	0.41	—
Aerated lagoon	1	30.35	—	11.61	—	0.38	—
All plants	43	15.76	13.43	11.28	10.49	0.70	0.23
				SS			
Conventional	18	14.92	10.53	16.02	18.61	0.86	0.38
Complete-mix	5	19.88	14.19	19.65	16.92	1.00	0.51
Step-feed/aeration	13	16.23	16.65	16.83	23.89	0.83	0.34
Contact stabilization	4	40.88	26.75	37.66	26.18	0.90	0.14
Extended aeration	1	8.82	—	5.28	—	0.60	—
Kraus	1	24.12	—	9.25	—	0.38	—
Aerated lagoon	1	58.79	—	18.71	—	0.32	—
All Plants	43	19.40	17.03	18.35	20.60	0.84	0.37

Table 4. Recommended Design Values for Effluent BOD and SS Concentrations in Order to Produce Stable Process

Process Type	BOD≤ (g/m^3)	SS≤ (g/m^3)
Step-feed/aeration	14.70	12.05
Conventional	14.50	11.63
Complete-mix	13.00	10.00
Contact stabilization	13.16	11.11

Variability of Activated Sludge Processes

Variations in the effluent quality from activated sludge processes are the result of a number of internal and external factors. In recent years, a considerable research effort has been directed toward examining process performance variations. Both experimental and analytical research studies have been conducted; however, most of the experimental studies have been carried out under laboratory rather than field conditions. Thus the results reported do not necessarily reflect conditions encountered in full-scale operations.

Nature and Sources of Effluent Variability

Several factors contribute to the perturbations observed in effluent quality. The following factors have been identified as being important.

1. Influent variables
2. Environmental conditions
3. Biological and operational parameters
4. Settling characteristics and clarifier design
5. Size of plant and type of process
6. Time effects
7. Human factors
8. Inherent process variability

Distributional characteristics and statistical data of these variables were determined for the plants studied. Correlation analysis has been used to investigate the extent to which variations in effluent quality are linked to variations in the other variables. Regression analysis techniques have been used to evaluate the contribution of a specific variable or set of variables in the effluent BOD and SS variations. Selected groups of variables were studied, both individually and in combination, to determine the individual linear effect as well as combined effect of each group of variables on effluent fluctuations. Detailed results of statistics as well as coefficient or correlations and regression analyses of the data are summarized in the main report. Only the summary results of the coefficient of determination for each regression study for some of these plants are given in this summary report (Tables 5 and 6). The coefficient of determination, R^2 (which is the square of correlation coefficient) is used to describe the proportion of variation in one variable that can be explained by the other.

In Tables 5 and 6, the most significant variables, those that explain at least 5 percent of effluent variations have been shown in parentheses. Other variables have less than a 5-percent effect on effluent variability. In those plants that have one or more missing variables in their data reports, regression analysis cannot be carried out because the variable group is incomplete; thus results are shown as blanks in these tables. The meaning of the coefficient of determination in Tables 5 and 6 is best explained by an example.

For instance, in Plant No. 1, only 3 percent of effluent BOD changes can be explained by input variables (Flow, BOD_i). Neither flow nor influent BOD_i has notable effect on effluent BOD. Wastewater temperature accounts for 36 percent of the variation.

Table 5. Regression Analysis Coefficient of Determination, R^2, for Effluent BOD and Selected Groups of Variables[a]

Plant Number	Input[b]	WTEMP	Bio. & Oper.[c]	SVI	Time	All Variables[d]
1	0.03	0.32	0.09 (Q_R)	0	0.22	0.48 (WTEMP)
2	0.03	0.01	0.29 (Q_R)	0.27	0.03	0.42 (SVI, MLSS)
3	0.05	0.14	—	0	0.07	0.21 (WTEMP)
4	0.16 (BOD_i)	0.15	0.25 (MCRT)	0.12	0.13	0.43 (MCRT, WTEMP, BOD_i)
5	0.30 (BOD_i)	0.01	—	0.10	0.15	—
6	0.25 (BOD_i)	0	—	0.11	0.13	—
7	0.17 (BOD_i)	0.02	—	0.04	0.02	—
8	0.11 (BOD_i)	—	—	0.03	0.06	—
16	0.34 (BOD_i, Flow)	0.30	0.21 (X_R)	0.11	0.04	0.40 (WTEMP)
17	0.37 (Flow)	0.38	—	0.08	0.40	0.61 (WTEMP, Time)
18	0.12 (Flow)	0.01	—	0.08	0	0.27 (Flow, Time)
19	0.01	0.12	—	0.04	0.29	0.40 (Time)
31	0	0	—	0	0	—
33	0.19 (BOD_i)	0.07	0.02	0.05	0.08	0.32 (BOD_i, SVI)
34	0	0.01	—	—	0.02	—
38	0.07	0.16	0.16 (MLSS)	0.06	0.14	0.32 (WTEMP)
39	0.12 (BOD_i)	—	—	0	0.01	—
40	0.14(BOD_i)	0.02	—	0.01	0.20	0.34 (BOD_i, Time)
41	0.10 (BOD_i)	0.03	0.05	0.01	0.04	0.13 (BOD_i)
42	0.07 (BOD_i)	0.13	—	0.01	0.08	—
43	0.03	0.07	—	0	0.07	—

[a] *Values in parentheses are the most important variable (greater than 5% significance) in explaining the total variation.*
[b] *Input loads: Flow, BOD_i.*
[c] *Biological and operational variables: MCRT, MLSS, X_R, Q_R.*
[d] *All variables: Flow, BOD_i, WTEMP, MCRT, MLSS, SVI, Time.*

Symbols: BOD_i = influent BOD. Q_R = return sludge flow. MCRT = mean cell residence time. WTEMP = water temperature. MLSS = mixed liquor suspended solids. SVI = sludge volume index. X_R = return sludge concentration. Q_W = wastage flowrate.

Biological and operation parameters can be used to explain only 9 percent of effluent BOD fluctuations, where return flow Q_R, is the most important operational variable in this plant. Other biological or operational parameters do not contribute to the dispersion of effluent quality significantly. In Plant No. 1, SVI measurement does not account for the effluent BOD variations at all. Time of the year can be used to explain 22 percent of changes in effluent quality, which most probably is due to temperature deviations. A combination of all groups of variables can be used to describe 48 percent of effluent perturbations; and among all variables, wastewater temperature is the most important factor. The remaining variation (i.e., 52 percent) in this plant is not explained by the available set of data. The unexplained variation may be caused by other variables not included in the regression list, such as inherent variability and human factors. Similar explanations will hold for all other plants.

Discussion

The contribution of each group of variables to effluent quality variations can be derived from Tables 5 and 6 as discussed below.

Input Variables - Considering all plants studied, input variables accounted for a maximum of 37 percent of the effluent BOD fluctuations, and in most cases, their contribution was less than 17 percent. In a number of plants, influent BOD and flow were not the causes of the fluctuations in effluent BOD at all. Generally, the effect of influent BOD was more notable than flow, and with three exceptions, flow usually was not the responsible factor for effluent BOD variations.

The coefficient of determination between effluent SS and influent variables was generally low. For Plant No. 17 the R^2 value was 0.29, but all other R^2 values were below 0.18. Flow was found to be be a more important factor than influent SS in describing effluent SS deviations. This result may be due to flow related effects on clarifier performance. In most cases, input variables were more responsible for effluent BOD variations than for effluent SS.

Wastewater Temperature - It was found that up to 38 percent of the effluent BOD variation and up to 27 percent of the effluent SS variation was caused by fluctuations in wastewater temperature. In many plants, temperature changes did not have any effect on effluent quality. The contribution of wastewater temperature in effluent variability was not dependent on the geographical area of the plant.

Biological and Operational Variables - Biological and operational variables (MCRT, MLSS, X_R, Q_R, Q_W) generally were not found to be significant factors in explaining the effluent quality variations. The total contribution of these variables to effluent BOD variations was less than 30 percent and in some cases, was close to zero. Their effects on fluctuations in effluent SS was generally greater than effluent

Table 6. *Regression Analysis Coefficient of Determination, R^2, for Effluent SS and Selected Groups of Variables*[a]

Plant Number	Input[b]	WTEMP	Bio. & Oper.[c]	SVI	Time	All Variables[d]
1	0.05	0.04	0.11 (Q_R)	0.01	0.01	0.21 (Flow, SS_I)
2	0	0.03	0.17 (Q_R)	0.18	0.03	0.22 (SVI, MLSS)
3	0.01	0.26	—	0.11	0.06	0.41 (WTEMP, SVI)
4	0.10 (SS_I)	0.12	0.36 (MCRT)	0.14	0.17	0.52 (MCRT, SVI)
5	0.02	0.01	—	0.04	0	—
6	0.01	0	—	0.03	0	—
7	0.05	0.05	—	0.03	0	—
8	0.05 (Flow)	—	—	0.04	0.03	—
16	0.13 (Flow)	0.01	0.16 (Q_R)	0.32	0.25	0.52 (SVI, Time)
17	0.29 (Flow)	0.14	—	0.04	0.21	0.33 (Flow)
18	0.18 (Flow)	0.27	—	0.18	0.17	0.44 (WTEMP, Flow)
19	0	0	—	0.01	0	0.05
31	0.07 (SS_I)	0.04	—	0.02	0.03	—
33	0.11	0.02	0.20 (MCRT, X_R)	0	0	0.26 (MCRT, Flow)
34	0.03	0.03	—	—	0.05	—
38	0.06 (Flow)	0.13	0.17 (MLSS)	0.03	0.13	0.31 (MLSS, Time, MCRT)
39	0.01	—	—	0.02	0.01	—
40	0.12	0.05	—	0	0.16	0.36 (Time, Flow)
41	0.07 (Flow)	0.12	0.11 (Q_R, MLSS)	0.07	0.10	0.22 (WTEMP, Flow)
42	0.03	0.05	—	0.02	0.02	—
43	0.05	0.05	—	0	0.05	—

[a] *Values in parentheses are the most important variable (greater than 5% significance) in explaining the total variation.*
[b] *Input Loads: Flow, SS_I.*
[c] *Biological and operational variables: MCRT, MLSS, X_R, Q_R.*
[d] *All variables: Flow, SS_I, WTEMP, MCRT, MLSS, SVI, Time.*

Symbols: SS_I = *influent suspended solids.* Q_R = *return sludge flow.* MCRT = *mean cell residence time.* WTEMP = *water temperature.* MLSS = *mixed liquor suspended solids.* SVI = *sludge volume index.* X_R = *return sludge concentration.* Q_W = *wastage flowrate.*

BOD and was in the range of 11 to 36 percent.

Sludge Settleability - Sludge volume index (SVI) was generally reported as a measure of sludge settleability. Changes in SVI would be expected to be reflected in effluent quality variations, and this was true to some extent. Twenty-seven percent of the effluent BOD fluctuation was explained by SVI variation in Plant No. 2, but the R^2 values were less than 0.12 in all other plants. In a number of plants, there was no correlation at all between these two variables. Similar statements can be made about the correlations between SVI and effluent SS.

Combination of Variables - When the effects of all the input, environmental, and operational variables were summed, between 13 and 61 percent of the effluent BOD and between 5 and 52 percent of the effluent SS fluctuations (depending on the plant) were explained. The remaining variations were unexplained (i.e., inherent or human factors as defined here).

From these results, it is clear that the variables that affect plant performance vary from plant to plant. Any single variable or group of them may account for the fluctuations in effluent quality in different plants. For example, in Plant No. 1, wastewater temperature was the most important variable, whereas in Plant No. 2, SVI and MLSS contributed the greatest amount to fluctuations in effluent BOD. The contribution of the remaining variables was less than 5 percent.

Examination of the results presented in Tables 5 and 6 leads to the conclusion that there were only a few variables that contributed significantly to the changes in effluent quality. Among all variables, wastewater temperature was the most notable variable in describing effluent variations. Other variables found to be significant (minimum significance of 5 percent) included time of the year, flow, SVI, influent BOD, MCRT, MLSS, and influent SS

The overall results of this phase of the study are insufficient to generalize about the variability of process performance. Inclusion of additional data, however, is unlikely to alter this conclusion, for a large dispersion exists among the plants that have been studied. Therefore, analysis of data must be carried out at each specific plant to identify the main causes of variation.

Sources of Effluent Variation Unexplained by the Available Data - Many causes of performance variation exist that cannot be explained on the basis of analysis of the available data. Included among these variables are true inherent variability such as presence of toxic materials, nature of biota in the system, human factors including system design, operation and maintenance procedures, loading factors, systems control capability, and sampling techniques. These causes of variation were not analyzed because data were not available. Considering the results obtained from the analysis of the available data, it is reasonable to conclude that little additional information would be gained from further study.

Process Control

Evaluation of the results presented here provides insight into the main sources of variation at a particular plant. To reduce fluctuations in effluent quality, for example in Plant No. 2, sludge settleability must be improved. In Plant No. 17, flow equalization might be used to reduce the perturbations observed in the effluent quality; in Plant No. 41, improvement of unidentifiable variables, such as human factors, might reduce effluent quality variations.

In practical applications, regulation of wastewater temperature and influent flow and concentration is difficult; consequently, improvement of operational procedures and those parameters related to the solids separating facilities appear to be the most promising and practical parameters available for process control.

Effluent Discharge Standards

The objective of this section is to examine and discuss the appropriateness of effluent discharge standards as they are currently established and to compare the current approach using arithmetic mean to an alternative approach using the geometric mean concentration value (GM) for setting effluent discharge standards.

Use of the Geometric Mean

As mentioned at the beginning of the summary, effluent BOD and SS data have a lognormal distribution. For a set of data that are lognormally distributed, the sample arithmetic mean X, cannot represent the central tendency of the data. The best measure of central tendency for the lognormal data is the geometric mean, which is defined as:

$$GM = \left(\prod_{i=1}^{n} X_i \right)^{1/n} \qquad (7)$$

Where: $\prod$ represents the product of all sample values, and X_i represents a sample of independent observations $X_1, X_2, \ldots, X_n$.

Present EPA standards for discharge effluent BOD and SS are based on arithmetic 7- and 30-day averages. These average values do not adequately represent the central tendency of a lognormally distributed data set. The geometric mean of the 7- and 30-day effluent quality data are a more appropriate measure of central tendency than the arithmetic mean and it is recommended to be used in setting discharge standards.

Stochastic Based Design and Standards

In view of the uncertainties in process design and operation, the performance of a given process will be uncertain to some degree. Therefore, design procedures should be based on a recognition of the uncertainties.

The best way to accomplish this is to incorporate probabilistic concepts and procedures in the design process and in setting discharge requirements. Use of probabilistic methods in setting discharge standards precluded the rational setting of parameter values that can never be exceeded. For example, setting maximum allowable values of BOD or SS for any single sample has no meaning if a measure of random variation in these parameters exists. Current EPA effluent discharge standards should be restructured based on stochastic concepts to permit individual parameter values to exceed the designated standard value a given number of times in a specified time period.

Probabilistic procedures can be formulated in such a manner as to provide a probabilistic basis for design, even with a deterministic standard. Given the natural variability of plant performance, it should be possible to determine what true average effluent quality must be maintained such that a standard can be met with some high (and predetermined) probability. In other words, the requirements should be rephrased to permit the parameter to exceed the designated value, say, one time in 3 years or one in 10 years. The required plant performance can then be calculated, using the reliability model developed in this study. It must be recognized that standards stated in this manner reflect actual performance characteristics and are not less restrictive than deterministic standards. Design examples and operational application of the results of this study are given in the main report.

The full report was submitted in fulfillment of Grant No. R805097-01 by the University of California under sponsorship of the U.S. Environmental Protection Agency.

Salar Niku is presently with Brown and Caldwell Consulting Engineers, Pasadena, CA 91109; Edward D. Schroeder, George Tchobanoglous, and Francisco J. Samaniego are with the University of California, Davis, CA 95616.
Jon Bender is the EPA Project Officer (see below).
The complete report, entitled "Performance of Activated Sludge Processes: Reliability, Stability and Variability," (Order No. 82-109 604; Cost: $14.00, subject to change) will be available only from:
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650
The EPA Project Officer can be contacted at:
Municipal Environmental Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, OH 45268

☆U.S. GOVERNMENT PRINTING OFFICE:1981--559-092/3354

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

Postage and
Fees Paid
Environmental
Protection
Agency
EPA-335

Official Business
Penalty for Private Use, $300

RETURN POSTAGE GUARANTEED

Third-Class
Bulk Rate